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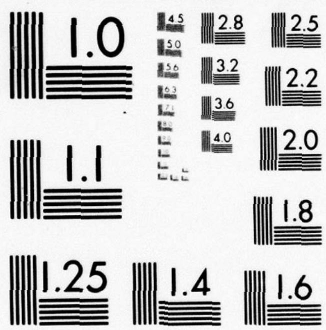

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Special Report 79-9

April 1979

ESTIMATED SNOW, ICE, AND RAIN LOAD PRIOR TO THE COLLAPSE OF THE HARTFORD CIVIC CENTER ARENA ROOF

R.K. Redfield, W.N. Tobiasson and S.C. Colbeck

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The roof of the Hartford, Connecticut, Civic Center Arena collapsed under an unknown load of snow, ice and rain early in the morning on 18 January 1978. Based on available meteorological and snow load measurements, estimates for the amount of load present at the time of failure are made using a number of techniques. In addition, previous maximum loads due to snow, ice or rain since the building was constructed are also estimated.

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PREFACE

This report was prepared by Robert K. Redfield and Wayne N. Tobiasson, Research Civil Engineers, Civil Engineering Research Branch, Experimental Engineering Division, and by Dr. Samuel C. Colbeck, Research Geophysicist, Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by the Structures and Materials Division, Center for Building Technology of the National Bureau of Standards.

Thaddeus C. Johnson and Michael A. Bilello of CRREL technically reviewed this report.

The authors are indebted to Dr. Bruce Ellingwood of the National Bureau of Standards for his support and to Dr. Charles Thornton of Lev Zetlin Associates for providing building design details and meteorological information.

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ESTIMATED SNOW, ICE, AND RAIN LOAD PRIOR TO THE COLLAPSE OF THE HARTFORD CIVIC CENTER ARENA ROOF

R.K. Redfield, W.N. Tobiasson and S.C. Colbeck

INTRODUCTION

The 2-1/2-acre roof of the Hartford Civic Center Arena collapsed during a snow and rain storm at 0418 hours on 18 January 1978. Fortunately the arena was unoccupied at the time of the collapse and no injuries resulted. However, the failure represented a significant economic loss to the community. Immediately following the collapse, the City of Hartford formed a committee to investigate the failure. Lev Zetlin Associates, Inc. (LZA) was engaged to conduct the structural investigation. A number of other investigative firms and individuals also provided information to the committee.

The National Bureau of Standards (NBS) through its Structures and Materials Division of the Center for Building Technology became involved in this investigation. NBS has studied numerous building failures but has not recently undertaken studies related to snow loads. Because of our involvement in snow load research[4,5,11,12], NBS asked CRREL to estimate the snow, ice and rain load on the arena roof at the time of collapse. NBS also asked CRREL to determine if this was the maximum load the roof experienced since it was constructed in 1973-74.

The load estimates developed in this report are based on a combination of published information, measurements and professional judgment.

THE ARENA ROOF

A 21-ft-deep steel space frame supported at four points formed the structural support for this roof as shown in Figure 1. All surfaces of the roof were sloped 1/4 in./ft to valleys with internal drains located on a line 90 ft in from the edge as shown in Figures 1 and 2. Under the full design live load of 30 lb/ft^2, the deflection of the space frame would be 6 in. upward at the corners and 13 in. downward at the center[3]. As the roof deflected under the live load, any water within 90 ft of the perimeter traveled to the drains on a slope somewhat greater than 1/4 in./ft. Any water on the central portion of the roof traveled outward toward the drains more slowly since the slope there was reduced below 1/4 in./ft.

The roof deck consisted of 3-in.-thick cementatious planks on subpurlins. Two inches of glass fiber insulation and a gravel-covered built-up membrane were placed above the deck. The thermal resistance (R)

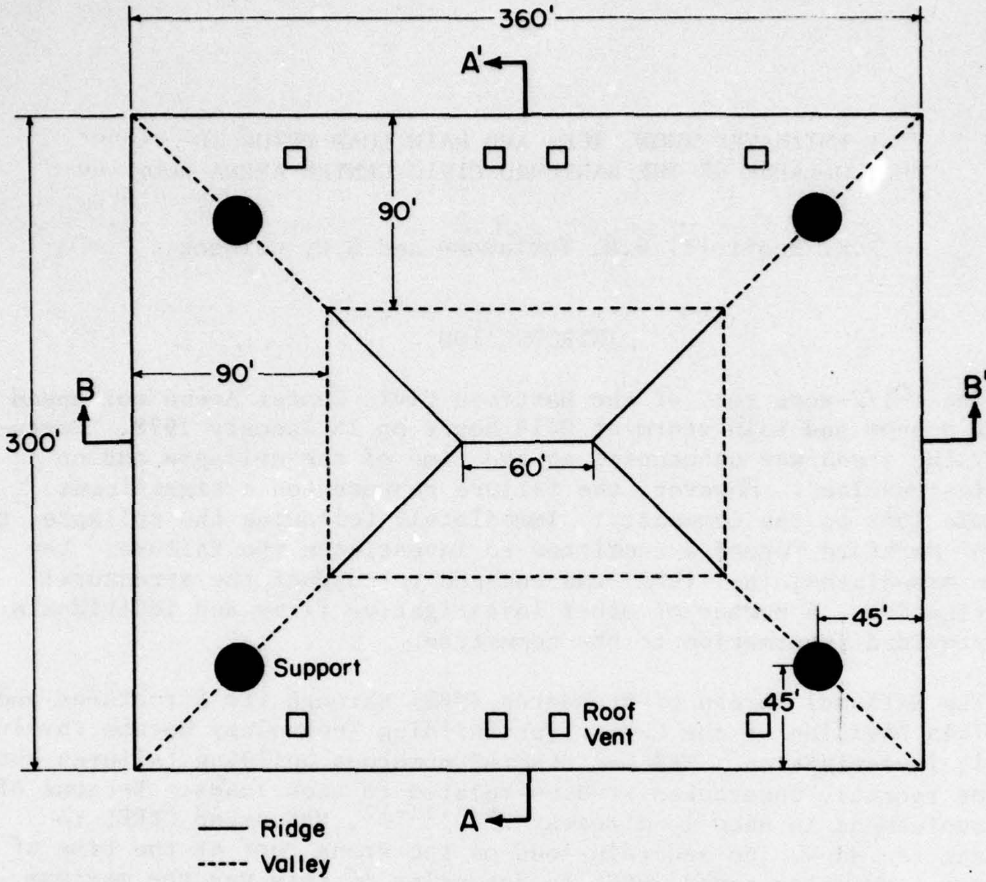


Figure 1. Plan view of arena roof.

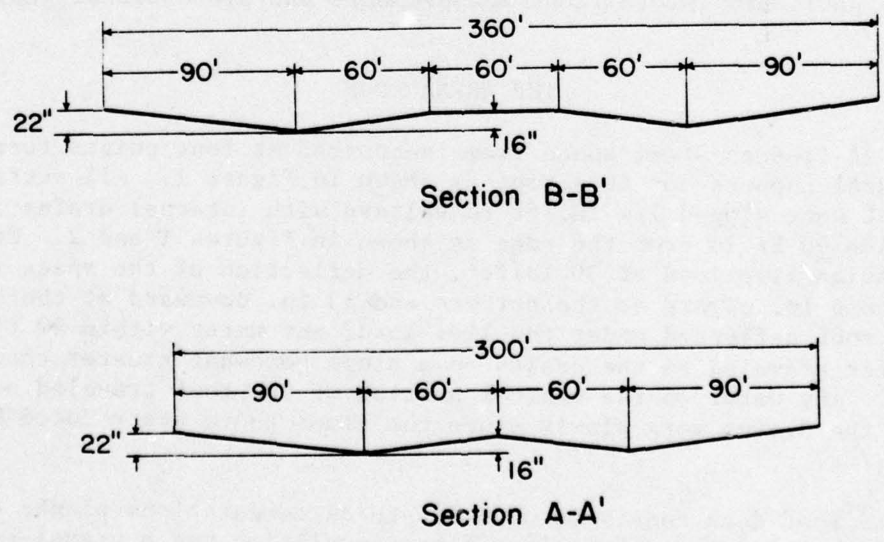


Figure 2. Geometry of arena roof surface.

of the roof was about 11 $ft^2 \cdot hr \cdot °F/Btu$. Tests conducted by Geisser and Associates Inc., consulting engineers, a day after the collapse indicated that the insulation and deck were relatively dry. Therefore, it appears no water was present in the roof to contribute to the roof live load.

The arena roof was about 25 ft higher than the roof over the rest of the Civic Center complex. The roof contained few obstructions and was not in the wind shadow of any other roof in the vicinity.

LOCAL WEATHER RECORDS

Sources of Weather Information

Weather records for the Hartford area are available at six locations. Records for National Weather Service stations are reported in the monthly publication, Climatological Data, New England[17]. These records include daily precipitation, temperature extremes, snowfall, and depth of snow on the ground for most stations. The daily form MF1-10B, Surface Weather Observations[14] and monthly summary form WS F-6, Preliminary Local Climatological Data[15] were obtained from the National Weather Service Office (NWSO) at Bradley International Airport in Windsor Locks, Connecticut. NWSO also provided a copy of form 612-14, Record of Climatological Observations[16] for Hartford Brainard Field (HBF), a secondary weather site. More detailed records not published in Climatological Data, New England are contained on these forms. Lev Zetlin Associates provided us with weather records collected by the Travelers Weather Service (TWS)[13], a commercial firm located in downtown Hartford. This information includes daily summaries and a monthly compilation. A description of the meteorological instrumentation available at each station and its location follows:

1. NWSO is located on the second floor of the FAA building. Instrumentation is located both near ground level and on the roof of the building. Ground elevation above sea level at the station is 169 ft. The temperature sensor, a tipping bucket rain gauge (4 ft aboveground), and the wind instruments (20 ft aboveground) are located adjacent to the building. A weighing rain gauge (47 ft aboveground) and an 8-in. rain gauge (45 ft aboveground) are located on the roof. According to station personnel, "depth of snow on the ground" measurements are made on the roof.

2. Elevations above sea level for the other National Weather Service (NWS) stations used in this study are as follows: Coventry, 480 ft; West Hartford, 275 ft; Hartford Brainard Field, 15 ft; Shuttle Meadow Reservoir, 410 ft. We assume that the rain, temperature, and depth of snow on the ground measurements, where available, are obtained on or near the ground at these stations.

3. Travelers Weather Service instruments are on top of the building at 250 Constitution Plaza, approximately 110 ft aboveground. Ground elevation above sea level is not reported but it appears to be approximately 50 ft based on the Hartford North, Connecticut, USGS Topographic Map[19]. Ground elevation at the Civic Center is about the same.

The locations of these weather stations relative to the Civic Center are shown on Figure 3. Travelers Weather Service is the closest station, being two blocks to the east. Because of its location and the detail available in the weather records, TWS serves as a primary source of climatic data for the study. Although NWSO at Bradley International Airport is 10.6 miles north of the Civic Center, the detail of the weather records collected there makes it an important source of data. Information from the rest of the NWS stations supplements the records from these two sources.

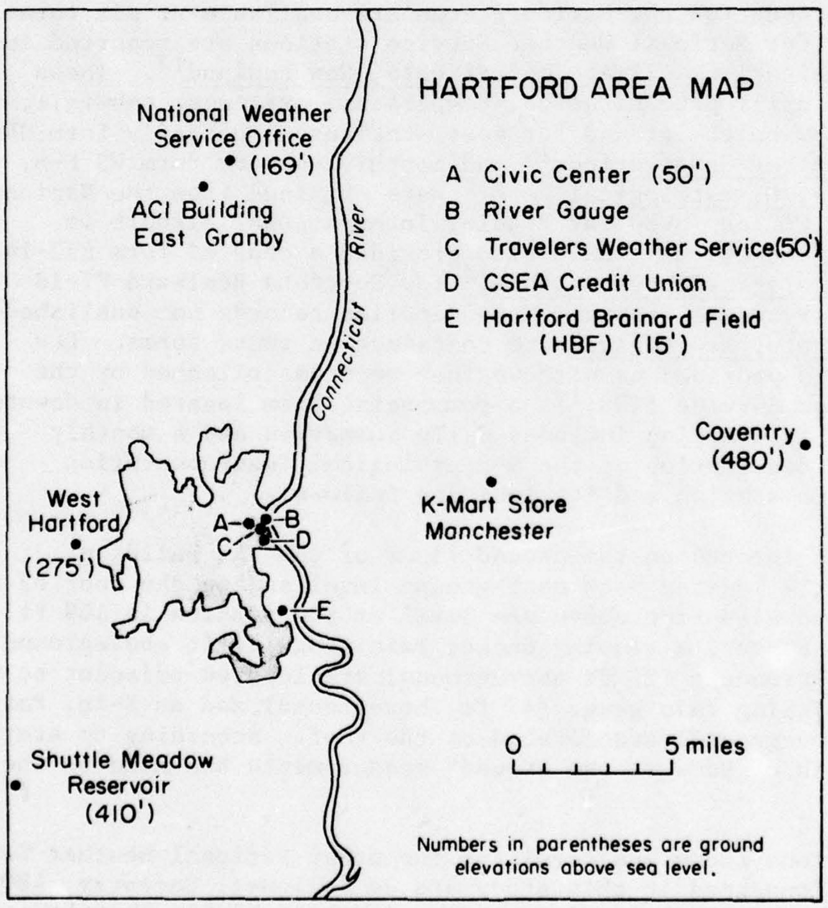


Figure 3. Map of the Hartford area with locations of weather stations, snow load measurement sites, and the Civic Center.

Comparison of Weather Records

Weather records vary from station to station because of local climatic differences, differences in instrumentation, and frequency of measurement; thus all stations used in the study do not have completely compatible records. Pertinent information is presented in the tables in this section. When possible, compatible records are presented so that direct comparisons can be made.

Records for the three stations which measure the depth of snow on the ground are summarized in Table I. The 24-hour precipitation and snowfall totals are also presented. Both the NWSO and TWS measure daily accumulations at midnight while at HBF the readings are made at 0800. Because of this, precipitation and snowfall comparisons should be made for each storm or storm period rather than daily. For example, the sum of 24-hour precipitation totals observed from midnight on 6 January through 0800 on 11 January at each station is as follows: NWSO, 2.25 in.; TWS, 1.56 in.; and HBF, 1.62 in. Such a comparison is useful in determining the spatial variation of the precipitation resulting from the passage of each storm.

The 24-hour snowfall records in Table I can be compared in a similar manner. The snowfall total for the 13-14 January storm was 7.3 in. at NWSO but only 4.5 in. at TWS (snowfall records at HBF for this storm are missing). For the storm of 17-18 January, NWSO measured a total of 9.7 in. of snow while downtown TWS measured 4.8 in. and HBF 3.0 in.

Depth of snow on the ground measurements are also presented in Table I. Maximum depth of snow on the ground resulting from the 13-14 January storm is reported as 7 in. by NWSO, 4.1 in. by TWS and 4 in. by HBF. The 17-18 January storm increased maximum snow depths to 15 in. at NWSO, 8.8 in. at TWS and 7 in. at HBF. Although both NWSO and TWS report "depth of snow on the ground," these readings are actually taken on the roof. Note that on 12 January all three stations report that the depth of snow on the ground is near zero. We assume that the snow load in the Hartford area was zero on that date and that the snow load on 18 January was the result of precipitation during the period of 13-18 January.

The 24-hour precipitation totals for all six stations in the Hartford area for the period 13-19 January are presented in Table II. The 24-hour maximum temperature measurements made by four of the stations and the time of day the measurements are taken are also presented. As discussed previously, it is only appropriate to compare precipitation totals for complete storm events since measurements are made at different times of the day. Table III summarizes the total precipitation measured at the six stations for the storms of 13-15 and 17-18 January.

Table I. Precipitation records for NWSO, TWS and HBF 1 - 19 January 1978.

	24-hour precipitation (in.) (includes melted snow)			24-hour snowfall (in.)			Depth of snow on the ground (in.)		
Jan.	NWSO	TWS	HBF	NWSO	TWS	HBF	NWSO*	TWS*	HBF
1	0.13	0.16	0	1.6	1.3	0	2	1.3	0
2	0.10	0.07	0.10	1.1	1.0	0	3	2.0	0
3	T	0	0	T	0	1.0	3	1.8	1
4	0	0	0	0	0	0	2	1.6	1
5	0	0	0	0	0	0	2	1.0	1
6	0	0	0	0	0	0	1	0.6	0
7	0.08	0.03	0	0.6	0.3	0	1	0.6	-
8	0.62	0.47	0	T	0	0	T	0	-
9	1.51	1.05	1.51	0.4	0.5	-	T	0.5	-
10	0.04	0.01	0.10	0.7	0.1	-	1	0.5	-
11	0	0	0.01	0	0	-	T	0.4	-
12	0	0	0	0	0	-	T	0.2	0
13	0.58	0.53	0.02	5.3	3.0	-	5	2.8	0
14	0.94	1.05	1.20	2.0	1.5	-	7	4.1	2
15	T	0	0	T	0	-	7	4.0	4
16	0	0	0	0	0	-	7	4.0	4
17	0.71	0.48	0	8.2	4.8	0	15	8.8	4
18	0.82	0.85	1.23	1.5	T	3.0	13	7.0	7
19	0.08	0.05	0.01	0.8	0.5	0	14	7.5	7

NWSO and TWS readings are as measured at midnight on the day noted.
HBF readings are measured at 0800 hours on the day noted.
- Missing record
T Trace (less than 0.01 in. of precipitation, 0.1 in. of snowfall).
* "Depth of snow on the ground" is measured on a roof at the NWSO and TWS.

Table II. Precipitation and maximum temperature comparisons for six stations in the vicinity of the Civic Center, Hartford, Connecticut.

	24-hour precipitation (in.)							24-hour maximum temperature (°F)							Measurement time (Eastern Std.)	
January	13	14	15	16	17	18	19	13	14	15	16	17	18	19	Precipitation	Temperature
Coventry	0.02	1.74	0.05	T	T	0.94	T	30	31	27	20	27	36	34	0800	0800
HBF	0.02	1.20	0	0	0	1.23	0.01	33	28	29	23	30	34	33	0800	0800
NWSO	0.58	0.94	T	0	0.71	0.82	0.08*	34	26	28	22	29	31	33	Midnight	0700
Shuttle Meadow Reservoir	0.08	1.75	0	0	T	1.76	0								0800	
TWS	0.53	1.05	0	0	0.48	0.85	0.05*	34	30	30	25	31	34	35	Midnight	0800
West Hartford	0.03	0.96	0.88	0	0	1.87	0.09								0800	

* Precipitation occurred after 0800.

T Trace (less than 0.01 in. of precipitation).

Table III. Comparison of total precipitation from the two storm events which occurred from 13 through 18 January 1978.

	Total precipitation+ (in.)		
	13-15 January	17-18 January	Total
Coventry	1.81	0.94	2.75
HBF	1.22	1.24*	2.46
NWSO	1.52	1.53	3.05
Shuttle Meadow Reservoir	1.83	1.76	3.59
TWS	1.58	1.33	2.91
West Hartford	1.87	1.96*	3.83

+ Includes water equivalent of melted snow.

* Total includes precipitation recorded at 0800 on 19 January but which fell after 0800 on 18 January.

Although a large portion of the differences in total observed precipitation is due to storm variability with location, some of the apparent variation can be attributed to rain gauge location and type. At both NWSO and TWS the recording rain gauges used for the tabulated values are located on the roof of a building and neither gauge is shielded. Furthermore, the readings on 18 January at NWSO were estimated from a rain gauge on the ground because of icing conditions on the primary rain gauge during part of the storm. HBF uses a recording gauge with a wind shield attached. The gauges at Coventry, Shuttle Meadow Reservoir, and West Hartford are nonrecording, unshielded gauges that are read once a day. These gauges and the one at HBF are located near ground level.

Maximum 24-hour temperature information for the period 13-19 January for Coventry, HBF, NWSO, and TWS is shown in Table II. Measurement times for Coventry and HBF are 0800. In order to present similar data, the measurements at 0700 for NWSO and 0800 for TWS have been presented. Average maximum temperatures for the four stations over the period are as follows: Coventry 29.3°F, HBF 30.0°F, NWSO 29.0°F, TWS 31.3°F. Temperatures measured at NWSO and Coventry are about 1°F colder on the average than those measured at HBF and 2°F colder than the TWS average. Since both HBF and TWS are downtown locations, with TWS located among the tall buildings, this rise in temperature can be attributed to the "heat island" effect of the city[10].

Detailed weather records for the period 13-19 January are available at NWSO and TWS. Since the type and amount of precipitation is critical to the analysis of rain and snow loads likely to have been present on the Civic Center during the morning of 18 January, this information has been studied in detail. It is summarized by storm in Tables IV and V. Each table contains an hour-by-hour listing of the weather records available at each station throughout the storm. "Melted precipitation" in inches includes rain and the water equivalent of all types of frozen precipitation. TWS reported only daily precipitation totals for these two storms although they do note the period during which precipitation was occurring. Snowfall readings in inches at both stations include the total accumulation for the period of record for all frozen precipitation. Precipitation type is reported at NWSO over the actual period of observation. This information is summarized in the tables by noting all precipitation types occurring within the hour regardless of whether the particular type of precipitation continued throughout the hour. TWS notes precipitation type each hour. Identification of the symbols used in the tables is noted at the bottom of each. A detailed explanation of each precipitation type can be found in Federal Meteorological Handbook No. 1, Surface Observations[18]. Average wind speeds are not available on the Surface Weather Observation forms acquired from NWSO. TWS reports the minimum and maximum wind speeds observed during each hour. The maximum observed peak gust in knots is reported by NWSO along with the time during the day it occurred. The peak gust is reported in Tables IV and V in mph at the end of the hour in which it occurred. Peak gusts greater than 20 mph are recorded during any hour in which they occur by TWS.

Table IV contains the summary of weather records for the storm beginning on 13 January and ending about midnight of 14 January. At both NWSO and TWS the storm began as light snow between 0400 and 0500 and gradually changed to other forms of freezing precipitation. Although temperatures at both sites remained below 32°F during the passage of the storm system, temperatures at TWS were consistently 2° to 4°F warmer than those at NWSO. Freezing precipitation other than snow occurred earlier and was more prolonged at TWS. Although the total precipitation at each station is nearly the same (1.52 in. at NWSO and 1.58 in. at TWS) NWSO reported 7.3 in. of snowfall while only 4.5 in. was recorded at TWS. Average wind speeds reported at TWS indicate that the winds increased during the day on the 13th reaching a maximum during the early morning hours of the 14th. Precipitation intensity at NWSO was also maximal at this time. Peak gusts up to 35 mph at NWSO and 39 mph at TWS were measured at the height of the storm.

The storm of 17-18 January is summarized in Table V. Similar to the earlier storm, precipitation began as snow and gradually changed to a mixture of frozen and liquid precipitation. Temperatures recorded at TWS are 3° to 5°F higher then those reported at NWSO. A significant

Table IV. Hourly weather summary for the 13-15 January 1978 storm at NWSO and TWS.

Day	Hour	Melted precipitation (in. of water) NWSO	Melted precipitation (in. of water) TWS	Snowfall* (in.) NWSO	Snowfall* (in.) TWS	Precipitation type NWSO	Precipitation type TWS	Temperature (°F) NWSO	Temperature (°F) TWS	Wind speed (mph) Average NWSO	Wind speed (mph) Average TWS	Wind speed (mph) Peak gust NWSO	Wind speed (mph) Peak gust TWS
13 Jan	0100	0	0	0	0			23	29		1-4		
	0200	0	0	0	0				28		2-4		
	0300	0	0	0	0				28		1-3		
	0400	0	0	0	0				28		1-3		
	0500	T				S-	S--		28		3-7		
	0600	0.01				S-	S-		26		3-6		
	0700	0.01		0.2		S-	S-	23-24	26		3-5		
	0800	0.03				S-	S-		27		4-7		
	0900	0.02				S-	S-		27		4-8		
	1000	0.02				S-	S-		28		6-11		
	1100	0.01				S-	S-		29		6-11		
	1200	0.02				S-	S-		29		8-14		
	1300	0.04		1.2		S-	S-	24-26	29		8-14		
	1400	0.01				S-	S-		30		8-15		
	1500	0.01				S-	S-		29		8-15		21
	1600	0.03				S-	S-		29		10-17		25
	1700	0.01				S-	S-		29		9-16		21
	1800	0.01				S-	SP-		28		9-16		21
	1900	0.01		1.5		S-	E-	25-26	27		10-18		28
	2000	0.03				S-	E-/ZR-		27		12-20		30
	2100	0.05				S-	E-/ZR-		26		13-31		30
	2200	0.08				S-/S	S/E-		26		12-21		28
	2300	0.12				S	S-/E-		26		14-23	29	32
	2400	0.06	0.53	2.4	3.0	S/S-/IP-	E	24-25	26		14-23		32
14 Jan	0100	0.10		T		S-/IP-	E+	24-25	27		15-26		36
	0200	0.19				S-/IP-	E+		28		18-28		39
	0300	0.26				S-/IP-/IP	E/S-		29		18-30	35	39
	0400	0.15				S-/IP/BS	E/S-		28		18-28		38
	0500	0.08				S-/IP/BS	E		28		16-28		35
	0600	0.04				S-/IP/ IP-/BS	L-/S-		28		15-25		34
	0700	0.02		1.6		S-/BS/F	L-/IP-	25-26	29		15-25		30
	0800	0.01				S-/BS/F/ ZR-	ZL-		29		15-25		31
	0900	T				F/ZR-	ZL-		30		14-26		33
	1000	0.01				F/ZR-ZL-	ZL--		30		15-26		31
	1100	0.01				F/ZL-	ZL--		30		15-25		31
	1200	T				F/ZL-	ZL--		30		15-25		31
	1300	0.01		.2		F/ZL-	ZL-	25-28	30		12-23		25
	1400	T		0		F/ZL-	ZL		30		12-24		27
	1500	0.02		0		F/ZL-	ZL		30		10-18		24
	1600	0.01		0		F/ZL-	ZL-		30		9-15		
	1700	T		0		F/ZL-	ZL-		30		8-13		
	1800	T		0		F/ZL-	ZL-		29		7-11		
	1900	T		0		F/ZL-	ZL-	26-28	29		7-12		
	2000	T				F/ZL-	ZL-	26	29		6-11		
	2100	T				F/ZL-	ZL-	26	29		4-9		
	2200	0.01				F/ZL-	ZL-	26	29		5-9		
	2300	0.01	1.05		1.5	F/ZL-/S-	ZL-	26	29		3-8		
	2400	0.01	0	0.2	0	F/S-		26	29		1-5		
15 Jan	0100	T	0	T	0	F/S-		25-26	29		0-4		
	0200	0	0	0	0				30		0-4		

IP	Ice pellets	--	Very light (flurry)
ZR	Freezing rain	-	Light
ZL	Freezing drizzle		Moderate
S	Snow	+	Heavy
BS	Blowing snow		
SP	Snow pellets		
E	Sleet		
F	Fog		
L	Drizzle		

Data for period

Missing data

* "Snowfall" includes all types of frozen precipitation.

Table V. Hourly weather summary for the 17-18 January 1978 storm at NWSO and TWS.

		Melted precipitation (in. of water)		Snowfall* (in.)		Precipitation type		Temperature (°F)		Wind speed (mph)			
										Average		Peak gust	
Day	Hour	NWSO	TWS	NWSO	TWS	NWSO	TWS	NWSO	TWS	NWSO	TWS	NWSO	TWS
17 Jan	0100	0	0	0	0			18-20	26		0-3		
	0200	0	0	0	0				26		0-2		
	0300	0	0	0	0				26		0-2		
	0400	0	0	0	0				26		1-4		
	0500	0	0	0	0				26		0-3		
	0600	0	0	0	0				25		1-4		
	0700	0	0	0	0			17-19	25		1-4		
	0800	0		0			S--		25		1-4		
	0900	T				S-	S-		25		2-5		
	1000	0.01				S-	S-		25		2-5		
	1100	0.02				S-	S-		25		3-6		
	1200	0.02				S-	S-		26		4-8		
	1300	0.03		0.9		S-/S	S-	18-23	27		6-11		
	1400	0.02				S-	S-		28		6-11		
	1500	0.03				S-	S-		28		6-12		
	1600	0.02				S-	S-		28		6-13		
	1700	0.02				S-	S-/S		29		6-13		
	1800	0.02				S-	S-		28		8-13		
	1900	0.03		2.0		S-	S-	23-25	28		8-13		
	2000	0.02				S-	SG-	25	28		7-12		
	2100	0.09				S-/S	S-	25	28		7-12		
	2200	0.12				S	S-/S	25	28		9-15		
	2300	0.12				S	S	25	28		10-15	20	
	2400	0.14	0.48	5.3	4.8	S	S-/E-	25	29		8-14		
18 Jan	0100	0.09		0.6		S/S-/ IP-	IP-/ZR-	25-27	30		9-15		20
	0200	(0.19)				S-/IP-/ ZR-/IP	IP-/R		33		10-18		21
	0300	(0.14)				S-/IP/ ZR-	IP-/R		34		10-18	24	22
	0400	(0.15)				IP/IP-/ ZR-	R+		34		10-18		21
	0500	(0.04)				IP-/ZR-	R-		34		10-18		21
	0600	(0.04)	**			ZR-	R-		34		10-18		23
	0700	(0.02)		0.9		ZR-	ZR-	27-31	33		8-18		24
	0800	(0.05)				ZR-	ZR-		33		8-15		
	0900	(0.05)				ZR-/ZL-	ZR--		32		6-13		
	1000	(T)				ZL-	ZL-		32		6-13		
	1100	(0.04)				ZL-/ZR-/ F	ZL-/S-		31		7-14		
	1200	(0.01)	0.85		T	ZR-/F/ ZL-/S-	IP-/S-		32		6-13		
	1300	(T)	0	T	0	ZL-		29-31	34		6-13		
	1400	0	0	0	0				35		6-13		

* "Snowfall" includes all types of frozen precipitation.

** TWS reported that 0.72 in. of precipitation had occurred as of 0545 (measurement beginning at midnight). "Estimated" values from the NWSO through 0600 total 0.65 in.

--	Flurry	S	Snow	T	Trace (less than 0.01 in. of precipitation, 0.1 in. of snowfall).
-	Light	IP	Ice pellets	○	Data for period
	Moderate	E	Sleet		
+	Heavy	ZL	Freezing drizzle		
		R	Rain		
		ZR	Freezing rain		Missing data
		SG	Snow grains		
				()	Values estimated from other gauges due to ice buildup.

difference in the 17-18 January storm, however, is that TWS reports temperatures above 32°F beginning at 0200 on 18 January. The temperature remained at or above 32°F at TWS until the end of the precipitation at noon except for the 1100 reading which was 31°F. The maximum temperature recorded for the same period by NWSO was 31°F. A period of rain was reported at TWS from before 0200 until 0600. Note that heavy rain was falling at TWS at 0400. Wind speeds again increased during the onset of the storm but the intensity of winds was less than in the previous storm. Peak gusts of 24 mph were recorded at both NWSO and TWS during the morning of 18 January.

Snow Loads Calculated from Local Weather Records

Based on the information presented in Tables I-V, a probable snow load present on the Civic Center roof at 0418 on 18 January 1978 can be calculated. Since NWSO, TWS, and HBF indicate near-zero depths of snow present on 12 January (Table I), we assume that the roof was essentially free of snow, ice, and water loads as of 12 January. This implies that any snow, ice, or rain previously on the roof had been removed by sublimation, evaporation and drainage. No direct information exists to verify our assumption that the drains were functioning at that time; however, no evidence exists to support the contrary assumption that drains were clogged and water ponds had formed on the roof.

The Civic Center Arena roof was about 90 ft aboveground. Due to its close proximity to the 110-ft-high roof where TWS data are collected, the TWS records should accurately describe weather conditions on the arena roof. We assume, then, that despite the possibility of any differences in exposure and thermal characteristics, the depth of snow on the two roofs was the same.

The onset of the storm of 13-14 January occurred sometime before 0500 on the 13th (Table I). TWS reported light snow accompanied by temperatures ranging from 26° to 30°F and average wind speeds increasing from as little as 3 mph to as high as 17 mph up to 1800 (Table IV). From 1800 until midnight, sleet, freezing rain, and snow with temperatures of 26° to 27°F and average wind speeds of 10 to 23 mph were recorded. As of midnight on 13 January, 0.53 in. of total precipitation including 3.0 in. of snowfall had resulted in a depth of snow at TWS of 2.8 in. (Table I). Peak gust winds greater than 20 mph were measured each hour after 1400, increasing to 32 mph at midnight. Despite the high winds, we assume that a relatively uniform deposition of 2.8 in. of wet snow accumulated on the arena roof as of midnight of 13 January. In comparison, NWSO measured 0.58 in. of total precipitation, including 5.3 in. of snowfall as of midnight (Table I). Temperatures, however, were colder at NWSO (23° to 26°F), and all but a small portion of the precipitation was reported to be snow.

From midnight until 0700 on 14 January TWS reports that sleet, snow, ice pellets, and drizzle fell with temperatures of 27° to 29°F and average winds of 15 to 30 mph. Peak gusts up to 39 mph were recorded during the early morning when the storm was most intense. Between 0700 and 2300, when precipitation ended, light freezing drizzle was reported. Temperatures were 29° or 30°F for this period with gradually decreasing wind speeds. Total precipitation of 1.05 in. and snowfall of 1.5 in. was measured for the day. The depth of snow at TWS at midnight on 14 January was 4.1 in. Concurrent measurements made at NWSO indicated that 0.94 in. of precipitation and 2.0 in. of snowfall had accumulated during the day resulting in a 7-in. depth of snow. Temperatures at NWSO ranged from 24° to 28°F. We believe that about 4 in. of wet, dense snow was uniformly distributed on the Civic Center arena roof as of midnight on 14 January. The 0800 measurement made at HBF on 15 January of a 4-in. depth of snow on the ground is further indication that this assumption is reasonable.

Total precipitation for this storm as measured at TWS was 1.58 in. Precipitation measurements made at the five NWS stations within a 17.5-mile radius of the arena ranged from 1.22 to 1.87 in. (Table III) and averaged 1.65 in. We believe, however, that the TWS reading best describes conditions at the Civic Center. Since all the precipitation occurred at subfreezing temperatures and essentially all the precipitation was frozen or "freezing," no melt or runoff would have occurred. Therefore, we expect that the uniform load generated by this storm was about 8 psf (i.e. 1.58 in./12 in. x 62.4 pcf $\approx$ 8 psf). Since the 4 in. of snow on the roof had a water equivalent of 1.58 in., the average specific gravity of the snow would have been 1.58/4.0 = 0.395 (average density = 24.7 pcf) which is quite high. We expect, however, that the snow was far from homogeneous. The prolonged period of freezing drizzle at the end of the storm is likely to have formed a layer of glaze at the top of the snowpack. The below-freezing temperatures and lack of rain suggest that there was no lateral movement of water in the snow or at the roof surface as a result of this storm.

Retention of precipitation within the snowpack also is evidenced by records of river stage. NWSO reports the Connecticut River depth as of 0700 each day. This reading is plotted for each day in January in Figure 4. The effect of the runoff caused by the passage of a low pressure system on 8-10 January which continued up through the Connecticut River drainage basin in Massachusetts, New Hampshire, and Vermont is indicated by the rise and fall of river stage from 9 through 16 January. The system caused temperatures over the drainage basin to rise to near 60°F in Connecticut and over 50°F almost all the way to Canada. It also produced from 1.5 to 3 in. of precipitation, most of which was rain. The combined snowmelt and rainfall runoff caused a significant rise in water level that peaked on the morning of 11 January as shown in Figure 4. Temperatures dropped to below freezing after the

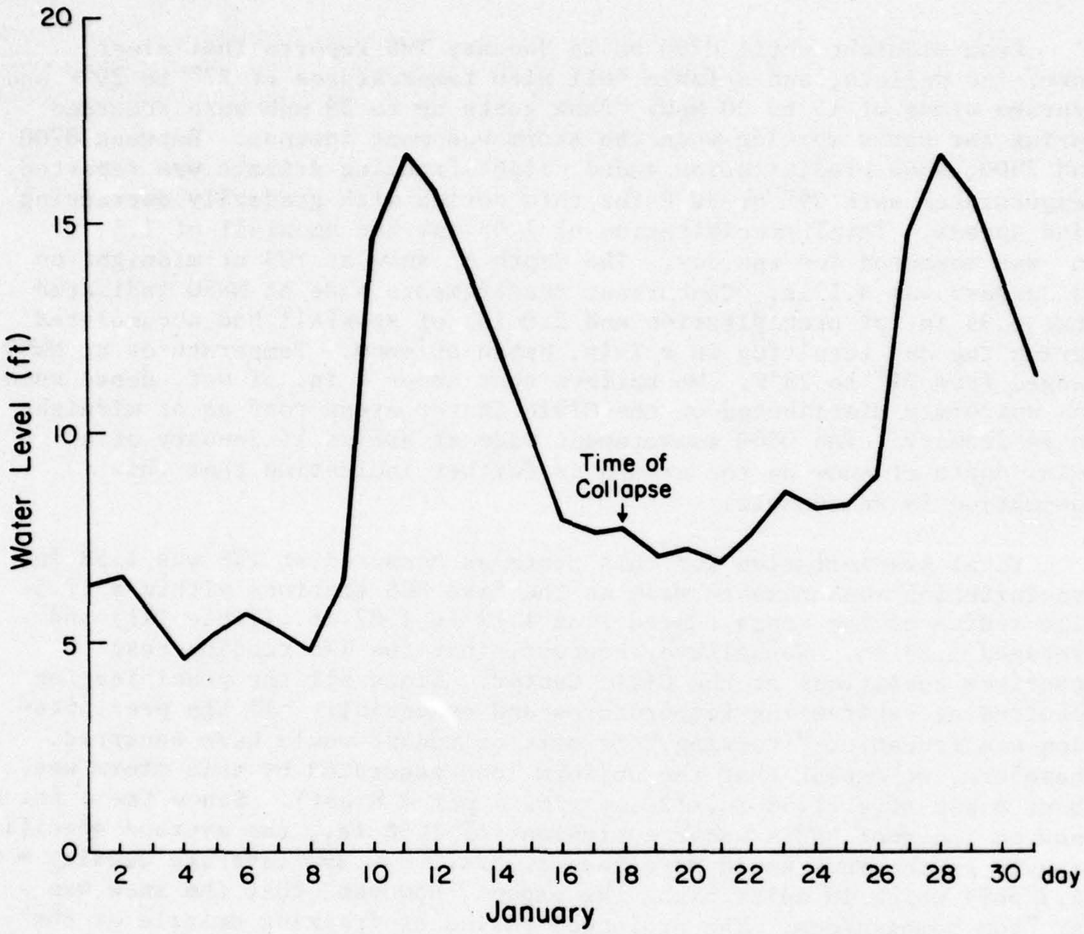


Figure 4. Connecticut River stage.

storm's passage and remained at that level through the 17th except for a few hours on the 12th. The accompanying steady drop in river level through the 16th suggests that no additional surface runoff was entering the river. This reinforces the conclusion that all precipitation occurring on 13-14 January remained in the snowpack created by that storm.

Weather on 15 January was partly sunny with decreasing cloud cover during the day and cold temperatures. From a high of 30°F at 0200, hourly temperatures dropped to 20°F at 0900 and rose only to 25°F at 1600. It is unlikely, therefore, that any melt occurred during the day on 15 January despite the sunshine (NWSO reported 91% possible sunshine during the

day). Since 4.0 in. of snow remained at TWS at midnight of 15 January and snow depths of 7 and 4 in. remained at NWSO and HBF, respectively, we conclude that the snow load on the arena remained constant at about 8 psf through the 15th.

Very few clouds were observed by TWS during the day on 16 January (97% possible sunshine at NWSO). From a low of 16°F at 0700, temperatures at TWS rose to 31°F by 1400 and remained at that temperature through 1700. Although still below freezing, it is possible that, due to solar radiation and building heat, a small amount of snowmelt may have occurred on 16 January. If, as we assume, there was a uniform snow cover on the arena roof 4 in. thick, the high albedo of the snow would have minimized the effects of the sun. Snow depths of 4.0 in. at TWS and 7 in. at NWSO as of midnight 16 January indicate that little or no melt occurred on those roofs since the last storm. The 4-in. depth at HBF also remained constant through 0800 on 17 January. The river gauge reading at 0700 on 17 January was only slightly lower than the previous day's measurement and still somewhat higher than it had been in early January (Figure 4). This could be explained by the river getting closer to its normal flow level, by continued ground water flow and, perhaps to a minor degree, by some snowmelt and runoff. We expect that the amount of snowmelt and runoff was small and that it was generated on pavements and other areas only partially snow covered. We expect that the snow load on the arena roof remained at about 8 psf until 17 January when a second storm took place in this area.

Snowfall began at TWS prior to 0800 on 17 January and continued until midnight when a mixture of snow and sleet was observed (Table V). Total precipitation recorded during the day was 0.48 in. which fell as 4.8 in. of snow. The depth of snow at TWS was 8.8 in. at midnight. The temperature ranged from 25°F during the morning to 29°F late in the day. Windspeeds increased from calm conditions at 0800 to average winds as high as 15 mph at midnight. Snow also fell all day at the NWSO with a total precipitation of 0.71 in. and snowfall of 8.2 in. recorded at midnight. Temperatures ranged from 18 to 25°F and the depth of snow at midnight was 15 in. Again assuming TWS measurements best describe the conditions downtown, it seems that there would have been about 8.8 in. of snow on the arena roof as of midnight on 17 January. This snow would have produced a load of about 11 psf (2.06 in./12 in. x 62.4 pcf $\approx$ 11 psf).

After midnight on 17 January, precipitation at TWS changed to a mixture of ice pellets, freezing rain, and, eventually, rain as temperatures increased. Light freezing rain and light ice pellets were reported at 0100 when the temperature was 30°F. At 0200 on 18 January, the temperature had increased to 33°F and precipitation changed to moderate rain and light ice pellets. The same combination of precipitation was occurring at 0300 but the temperature had risen to 34°F. At 0400, just prior to the arena roof collapse at 0418, heavy rain was falling and the

temperature was 34°F. At 0500, and through 0600, the rain had become light and the temperature remained at 34°F. From 0700 until the end of precipitation at noon the temperature ranged from 31° to 33°F and a mixture of freezing rain, freezing drizzle, ice pellets, and snow was reported. Average wind speeds were 6 to 18 mph through the period with peak gusts of 20 to 24 mph reported from 0100 through 0700. Average wind speeds were 10-18 mph and peak gusts 21 mph at both 0400 and 0500. Total precipitation for 18 January was 0.85 in. at TWS with only a trace of snowfall. Depth of snow at midnight had decreased to 7 in. NWSO records show a similar pattern except that the temperature range from midnight to 1300 when precipitation ended was 25° to 31°F. Freezing rain, ice pellets, snow, freezing drizzle, and fog were reported during the morning of 18 January but rain was not observed. Total precipitation for the day at NWSO was 0.82 in. and snowfall was 1.5 in. At midnight, a snow depth of 13 in. was reported. The 0800 readings at HBF on 18 January were: precipitation, 1.23 in.; snowfall, 3 in.; and snow depth, 7 in.

Based on the above information, it is likely that about 8 in. of wet snow was present on the arena roof when it collapsed at 0418 on 18 January. It was windy and raining heavily in downtown Hartford. Although TWS did not report hourly precipitation readings during the morning, they measured 0.72 in. of precipitation between midnight and 0545. NWSO, which estimated hourly values, reported that total precipitation was 0.65 in. from midnight up to 0600. Since the precipitation up to 0418 at NWSO was about 0.58 in., we estimate by proportion that about 0.64 in. of precipitation had fallen at TWS from midnight on 17 January until the time of the collapse. Although most of this precipitation was rain, all of it was probably absorbed by the snow on the roof. If this is so, we calculate that the load on the arena roof at the time of the collapse was about 14.0 psf based on TWS records (Table VI). The justification for the assumption that essentially all the rain was absorbed by the snow cover is discussed later.

Although the snowpack buildup at NWSO was significantly different from that which occurred downtown, the precipitation generated by each storm and the total precipitation up to the time of the collapse were similar at the two locations (Table VII). Note that the snow load generated at NWSO by the same approach as used for the TWS data is about 15 psf.

In addition to this comparison, the water equivalent of the snowpack is recorded at 1300 daily at NWSO (Table VIII). The 18.7-psf load for 18 January in Table VIII includes about 0.24 in. of water (1.2 psf) that occurred after the arena roof collapsed (Table V). The load at the time of collapse, estimated from the NWSO water equivalent records, would then equal 17.5 psf.

Table VI. Chronology of snow loads generated from TWS records.

Measurement time/day	Total precipitation at TWS (in.)	Estimated water equivalent on roof** (in.)	(psf)
Midnight, 13 January	0.53	0.53	2.8
Midnight, 14 January	1.05	1.58	8.2
Midnight, 15 January	0	1.58	8.2
Midnight, 16 January	0	1.58	8.2
Midnight, 17 January	0.48	2.06	10.7
0418, 18 January	0.64*	2.70	14.0

* Estimated from NWSO and TWS information.

** Assuming no runoff occurred and a uniform load was deposited.

Table VII. Comparison of precipitation totals for TWS and NWSO.

	TWS (in.)	TWS (psf)	NWSO (in.)	NWSO (psf)
13-15 January storm	1.58	8.2	1.52	7.9
17 January - time of collapse	1.12	5.8	1.29	6.7
	2.70	14.0	2.81	14.6

Table VIII. Snowpack water equivalent and concurrent depth of snow at the NWSO.

January	Depth of snow (in.)	Water equivalent* (in.)	"Ground snow load" (psf)
1	T	-	-
2	3	.2	1.0
3	3	.2	1.0
4	2	.2	1.0
5	2	.2	1.0
6	1	-	-
7	1	-	-
8	1	-	-
9	0	0	0
10	0	0	0
11	1	-	-
12	T	-	-
13	1	-	-
14	7	1.3	6.8
15	7	1.3	6.8
16	7	1.3	6.8
17	8	2.0	10.4
18	14	3.6	18.7
19	13	3.4	17.7

Water equivalent is recorded as of 1300, depth of snow values in this table are also the 1300 readings.

- Missing data.

* Water equivalent is measured only when at least 2 in. of snow is present.

NWSO is the only station in the Hartford area to report the snowpack water equivalent. Unfortunately, the water equivalent is not actually measured but is estimated from total precipitation, precipitation type, and "meteorological experience." The calculation of snow loads from

snowpack water equivalents generated in this manner is not expected to be very accurate. In addition, this value is also questioned because of a discrepancy in the NWSO data. As shown in Table VIII, the depth of snow increased only 1 in. from 1300 on 16 January to 1300 on 17 January. During the same period the water equivalent increased by 0.7 in. Table V shows that NWSO recorded only light snow during that period which had a water equivalent of 0.08 in. Detailed examination of the NWSO records reveals that the daily total of 0.71 in. of precipitation may have been inadvertently added twice. Subtracting this 0.71-in. (3.7-psf) potential error from the 17.5 psf value previously calculated generates a 13.8 psf load. This compares rather well with the other loads generated from TWS and NWSO records but it is still of questionable value.

SNOW LOAD MEASUREMENTS

Summary of Available Information

After the collapse of the arena roof, three organizations made measurements of roof and ground snow loads in the Hartford area. Unfortunately, no measurements of the snow load on the arena roof were made. Results are summarized below.

1. Lawrence F. Buck (of Buck & Buck, Engineers) measured the snow load on the flat roof of the C.S.E.A. Credit Union building at 0900 on 18 January. The building is located at 84 Wadsworth Street about five blocks from the Civic Center. Snow on this roof was about 5 1/2 in. deep and Buck stated that this snow "consisted of two layers of ice and snow and a top layer of somewhat loose snow." The bottom 1 1/2 in. was "completely saturated." Buck measured a "uniform snow load" of 16.4 psf and estimated that an additional 0.5 to 1.0 psf should be added to this weight to account for the water in the bottom layer. Therefore, the probable uniform load is 16.9 to 17.4 psf. Buck also inspected the drains located at the corners of the roof and found them to be snow-covered but not frozen.

2. R.F. Geisser & Associates, Inc., Consulting Engineers, obtained snow samples on the lower roof of the Civic Center complex adjacent to the failed arena roof. The measurements were made during the day of 19 January. The weights of the four samples are as follows:

Snow	Sample	1	=	11.67 psf
"	"	2	=	9.73 psf
"	"	3	=	11.31 psf
"	"	4	=	10.30 psf

The average load was 10.8 psf. According to Lev Zetlin Associates the roof where these samples were obtained is an insulated membrane roof.

This roof is about 25 ft below the elevation of the arena roof. Drifts are likely to occur on portions of lower roofs near changes in elevation. Other portions of lower roofs may be scoured of some snow by wind channeling.

3. Ground snow load measurements were made across the street from the Civic Center, in Manchester, and in East Granby (Fig. 3) on 19 January by CRREL. Roof snow loads were also measured in Manchester and in East Granby. At all but one location snow sampling tubes were inserted into the walls of test pits dug in the ground or roof snowpack to determine the density of the snow layers. A stratigraphic profile was made and ice layers were defined. Solid ice was assigned a density of 57.2 pcf. Snow tubes could not be inserted into the ice and snow on the ground in Manchester. Instead a block sample of known dimensions was removed and weighed.

In East Granby, ground and roof snow load measurements were made at the office of ACI, Inc. This location is close to NWSO and was selected to permit comparisons with NWSO weather records. The ground snow load was measured on a flat, open area near the company parking lot. The area appeared to have a uniform snow cover. The roof snow load was measured on the flat exposed roof of the ACI building. Some minor drifting was present on the roof but the measurement was made in an area with average conditions. The snow profiles and loads measured at these two locations are presented in Figure 5.

Permission to measure snow loads on the Civic Center Arena roof was not granted, but photographs were taken of the snow on portions of the failed roof from vantage points near the arena. One photograph (Fig. 6) of the snow remaining on a corner of the arena roof shows what appears to be a shallow, two layer, uniform-depth snow cover. The snow load on the ground was measured in the courtyard of the church located on the corner of Ann and Church Steets near the entrance to the arena. The courtyard is rather small and is encircled by a solid rock wall. Although it appeared that no snow had been shoveled into the area where the sample was taken, some drifting was noted. Results are presented in Figure 7.

Ground and roof snow loads were measured at the K-Mart store in Manchester, Connecticut, about eight miles east of the arena. Snow on the ground at that location was different than that encountered at the other two locations where samples had been taken. Core samples could not be taken because of the amount of ice in the snow profile. Instead, a block of material of known dimensions was removed and weighed. Results are presented in Figure 8.

A portion of the roof of the K-Mart building had also collapsed during the early morning of the 18th. That roof was essentially flat with a slight slope to the rear of the building for drainage. The roof

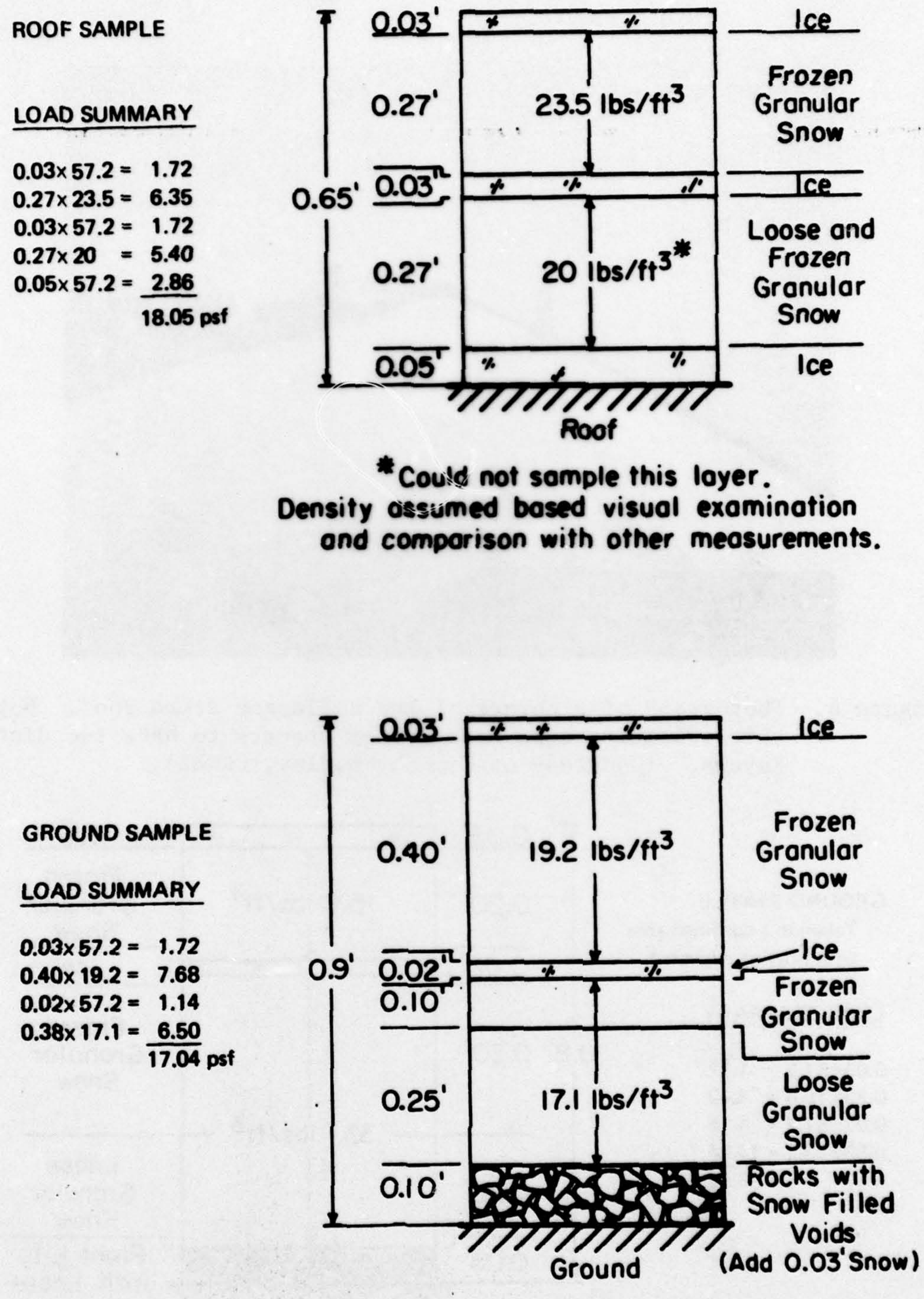


Figure 5. Snow samples - ACI Building, East Granby, Connecticut - 19 January 1978.

Figure 6. Photograph of a corner of the collapsed arena roof. Note that remaining snow near corner appears to have two distinct layers. (Courtesy of Timothy Dudley, CRREL).

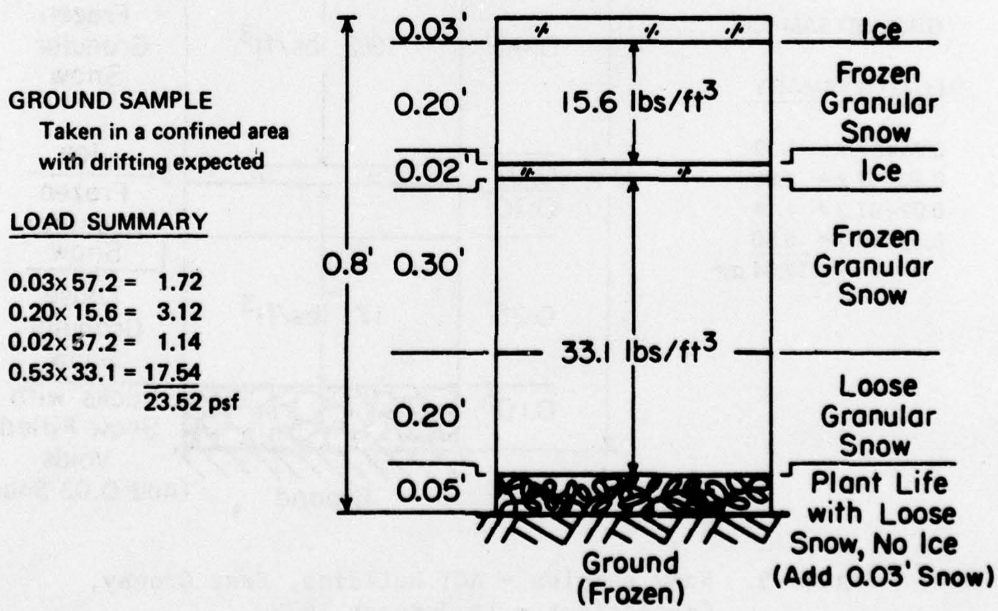
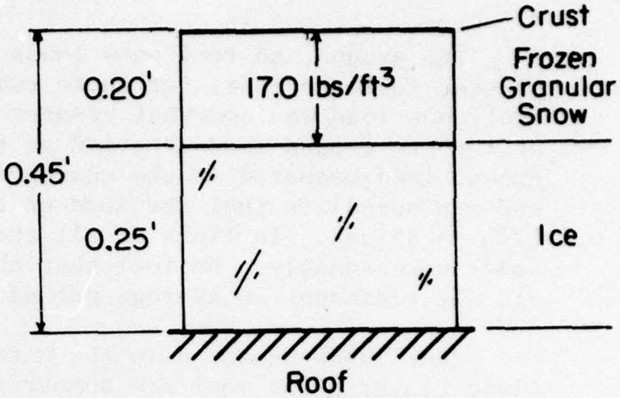


Figure 7. Ground snow sample adjacent to the Civic Center Arena - 19 January 1978.

ROOF SAMPLE

LOAD SUMMARY

0.20 × 17.0 = 3.40
0.25 × 57.2 = 14.30
17.70 psf



GROUND SAMPLE

No tube samples were obtained. A single block sample was obtained of all snow and ice.

Snow and ice load	14 psf	
Estimated water load	1-3 psf	
	15-17 psf	

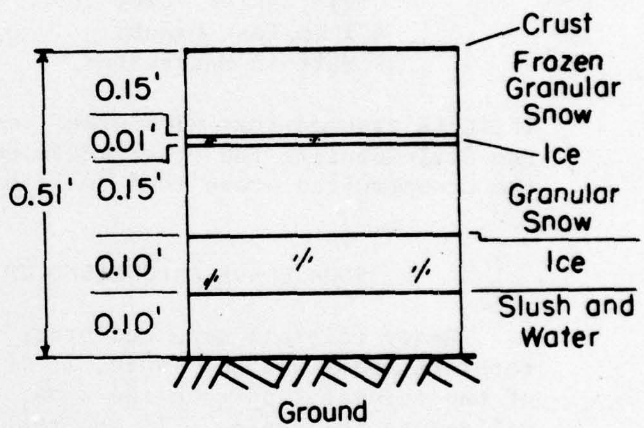


Figure 8. Snow samples - K-Mart Store, Manchester, Connecticut - 19 January 1978.

was exposed to winds and was free of obstructions except for a mansard across a portion of the main facade. Some minor drifting was present in the vicinity of the mansard. The failed area was near the main facade but off to the side of the mansard. The roof sample (Figure 8) was taken adjacent to this area.

Estimated Arena Roof Load Based on Snow Load Measurements

It is common to consider that only a portion of the ground snow load will accumulate on exposed roofs. For most unobstructed flat roofs Canadian[2] and American[1] standards use 80% of the ground load to establish design roof loads. Unobstructed flat roofs exposed to wind on all sides are designed to hold only 60% of the ground load.

The ground and roof snow loads measured in East Granby and Manchester indicate that, for these two storms, the reverse was true: the roof snow load was somewhat greater than the ground load. If the ratio of roof to ground load observed at these two locations is applied to the ground load measured in the churchyard adjacent to the Civic Center, one can speculate that the load on the arena roof could have been as high as 25 psf. In light of all the other information available this seems unreasonable. We feel that the churchyard ground load probably did not represent an average ground load because of drifting.

Roof loads measured in the Hartford area after the collapse of the Civic Center Arena roof are summarized below:

CSEA Credit Union in Hartford	17.4 psf
Civic Center lower roof	10.8 psf (average)
ACI in East Granby	18.0 psf
K-Mart in Manchester	17.7 psf

If it is assumed that wind scour reduced the loads on the low roof of the Civic Center, the other measurements suggest that the snow load on the unobstructed arena roof could have been 17 to 18 psf.

SNOW LOADS CALCULATED USING A RAIN-ON-SNOW MODEL

Heavy rainfall occurred prior to the roof failure and, while the total rainfall was not large, it is important to consider the movement of the rainwater through the snow, over the roof surface, and along the valleys to the drains. If the roof drains were blocked and if the rainwater moved quickly through the snow, the rainwater could have collected in the roof valleys where large concentrated loads could have occurred. In the following analysis, we first route the rainwater through the snow and then compare our conclusions with hydrological runoff as indicated by the local river stage.

Recent studies of wet snow have led to the development of a model which predicts the water retention in and water flow through roof snowpacks[4,5]. The model considers such parameters as depth, porosity, temperature, and permeability of the snow on the roof, the duration and intensity of the rainstorm, and the size, slope, and shape of the roof. The model has the capability of forecasting maximum probable conditions but treats combinations of existing conditions as well. Using available meteorological information and snow stratigraphy data, the rain-on-snow model was used to estimate the probable amount of runoff resulting from the storms of 13-15 and 17-18 January.

Precipitation in the first storm was reported to be almost entirely frozen (snow, sleet, ice pellets) or freezing (freezing rain, freezing drizzle). Using TWS records, we assume that the total measured precipi-

tation (1.58 in.) which included 4.5 in. of snowfall resulted in a roof snowpack with a uniform depth of about 4 in. Because of the long period of freezing drizzle at the end of the storm, it is likely that the surface of the layer was glazed. The base of the snowpack may have had a layer of refrozen water. Because of the small amount of liquid water produced by the storm and the subfreezing temperatures that prevailed, we assume no runoff occurred during this storm or during the two days before the second storm.

The storm of 17-18 January began as snow and changed to a mixture of rain, freezing rain, ice pellets, and sleet. Essentially all the precipitation on 17 January at TWS was snow. Using TWS values, 4.8 in. of new snow which had a water equivalent of 0.48 in. fell up to midnight. We assume the snowpack on the arena at midnight on 17 January consisted of two layers of snow and ice having a uniform depth of 8.8 in. We estimate the total precipitation at the arena from midnight until 0418 on 18 January as 0.64 in. which was distributed in an unknown manner between frozen and liquid precipitation. For the most severe case, we assume that all 0.64 in. fell as rain in 4.3 hr. or 0.149 in./hr. This liquid would have penetrated the upper layer of new snow fairly uniformly with an assumed liquid saturation of about 10% of the pore volume as indicated by field and laboratory studies of water flow through snow[6,7]. We assume that the temperature of the snow was below freezing but the amount of liquid refreezing within the snow was negligible. Using the density of ice as 57.2 pcf and the density of the new snow as 6.2 pcf*, the snow porosity was $1 - \frac{6.2}{57.2}$ or 0.89. Liquid retention of the fresh snow can now be determined by multiplying the snow depth by the water saturation and by the porosity. The liquid retention of the upper layer, then, is 0.43 in. Therefore, of the 0.64 in. of rain, 0.21 in. penetrated through the upper layer to the lower 4-in.-thick layer.

If, as we expect, a layer of glazed snow or ice formed at the boundary between the layers, some of the rain would have been retained there. If the ice were impermeable, the liquid would have ponded on that layer and, eventually, lateral movement to the drains above the lower layer of snow could have occurred. From the stratigraphy of the snowpacks observed after the storm and from our experience, however, we expect that this boundary ice layer was not completely impermeable or otherwise a more substantial layer would have been observed. It is also unlikely that the layer of refrozen water at the base of the snowpack or the ponded water on the roof at CSEA on the morning of the 18th would have been observed unless there was percolation through the thin ice layer. Although it is unlikely that the liquid penetration of the lower layer would have been uniform, we will assume for the moment that all of the lower layer of snow on the entire roof was wetted with

*0.48 in. water/4.8 in. snow = 0.1 specific gravity x 62.4 pcf = 6.2 pcf density.

the 0.21 in. of liquid. Using data from TWS records, the density of this layer was (1.58 in./4 in.) x 62.4 pcf or 24.6 pcf and its porosity was (1 - 24.6 pcf/57.2 pcf) = 0.57. To determine the water saturation as a fraction of pore volume on the assumption that the 0.21 in. of liquid wetted the entire lower layer, we can use the following relationship:

water saturation = available liquid (depth of snow x porosity).

Accordingly, we estimate that the water saturation of the lower layer was no more than 0.092. Since the lower layer was unlikely to have had a water saturation above 0.1, there was an insufficient amount of liquid water in the lower layer of snow to expect lateral flow over the roof surface. Therefore, it is our opinion that only a small amount of rainwater could have reached the roof valleys by the time of failure. If we assume that much less than 100% of the area of the two layers was wetted, some runoff would be predicted. However, since not all of the 0.64 in. of precipitation from midnight to 0418 was liquid, our assumption about the uniformity of the fluid flow is offset by our assumption about the uniformity of the precipitation. We conclude, then, that little lateral movement of water was likely on the arena from 13 January to the time of failure. Snow loads previously calculated from local weather records are consistent with these conclusions. The load on the arena roof can be assumed to approach the total precipitation from the two storms up to the time of failure, i.e. 14 psf (Table VI). The decreasing hydrological runoff in the Hartford area, as indicated by the decreasing river stage for several days following the failure (see Fig. 4), supports this conclusion.

MAXIMUM ROOF SNOW LOADS PRIOR TO JANUARY 1978

The history of water equivalent values reported by NWSO can be used to decide if the snow load that occurred on 18 January 1978 was the maximum roof load during the life of the Civic Center. Although these values are taken outside of Hartford and are estimated rather than measured, they do provide a basis for estimating the maximum snow load ever present on the arena roof. Maximum monthly water equivalent values from 1974, when the Civic Center was constructed, through January 1978 are presented in Table IX. The January and February 1977 loads of 10.4 psf and 12.0 psf, respectively, are the next highest loads but neither is close to the 18.7 psf NWSO water equivalent value reported on 18 January 1978.

Records from NWSO and TWS for the period 25 December 1976 - 28 February 1977 are compared in Table X. Daily values for total precipitation, snowfall, maximum and minimum temperature and depth of snow on the ground for each site are presented as well as the water equivalent

Table IX. Maximum monthly snowpack water equivalent reported by the NWSO for the period of November 1974 through 18 January 1978.

Winter	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
1974-75	0	2.6	3.1	2.1	0	0
1975-76	0	9.4	7.3	1.6	3.6	0
1976-77	0	2.1	10.4	12.0	3.1	0
1977-78	0	3.1	18.7			

information from NWSO. Review of this information indicates that the snowpack was accumulating from 25 December 1976 to 5 February 1977 and then declining to zero by the end of February. It appears that two dates are of particular importance: 16 January when the depth of snow on the ground reached a maximum at both stations and 5 February when the maximum water equivalent at the NWSO occurred. The likely water equivalent in downtown Hartford has been developed on these two dates from the records in Table X. Less confidence is placed in this estimate than that done previously for January 1978 since loads built up over a much longer period.

The period between 25 December 1976 and 16 January 1977 produced 2.55 in. of total precipitation of which 22.2 in. was snowfall at NWSO. During this same period 3.01 in. of precipitation, of which 20.0 in. was snowfall, occurred at TWS. Almost half of the precipitation came on 10 January when 1.18 and 1.36 in. were reported at NWSO and TWS, respectively. It was quite cold during the period with minimum temperatures below freezing daily and maxima staying below 40°F at both sites. The few periods of above-freezing temperatures produced some melt, but, since they were brief periods, it is expected that much of the melt would have been retained in the snowpack itself. This is reflected in NWSO water equivalent records which fluctuate during the period but reach a maximum on 10 January at 1.6 in. (8.6 psf). A slight decrease to 1.4 in. (7.3 psf) despite increasing depth of snow occurred up to the 16th. This water equivalent estimate may be somewhat low. The additional precipitation reported at TWS downtown (0.46 in.) indicates that the water equivalent at the arena would have been greater than NWSO records indicate despite the somewhat higher temperatures and shallower snowpack. We estimate the snowpack water equivalent at the arena was 2.3 in. (12.0 psf) as of 16 January 1977.

During the period 17 January through 5 February 0.70 and 0.71 in. of precipitation were reported by NWSO and TWS, respectively. Snowfall totaled 8.1 in. at NWSO and 9.0 in. at TWS. Temperatures were somewhat higher during the period but minima below freezing were observed every

Table X. Comparison of NWSO and TWS data for 25 December 1976 through 28 February 1977.

	Precipitation (in. of water)		Snowfall (in.)		Temperatures ([F]) Minimum		Temperatures ([F]) Maximum		Depth of snow on the ground (in.)		Water equivalent (in.)
	NWSO	TWS	NWSO	TWS	NWSO	TWS	NWSO	TWS	NWSO	TWS	NWSO
25 Dec	0.03	0.06	0.3	0.5	15	22	38	41	0	0.5	0
26 Dec	0.25	0.45	3.0	3.0	23	28	37	37	3	2.0	0.3
27 Dec	0	0	0	0	10	15	26	28	3	2.0	0.2
28 Dec	0.10	0.07	1.0	1.0	10	16	19	24	2	3.0	0.3
29 Dec	0.11	0.08	1.3	1.4	15	20	26	30	3	4.0	0.4
30 Dec	T	0	T	0	11	14	20	20	4	4.0	0.4
31 Dec	0.02	0.08	0.7	1.0	13	16	20	23	5	4.5	0.4
1 Jan	T	0.02	0.2	0.2	11	14	23	24	5	4.0	0.4
2 Jan	0	0	0	0	16	23	35	36	5	3.5	0.4
3 Jan	0	0	0	0	7	17	30	33	4	3.0	0.3
4 Jan	T	T	T	T	19	28	36	38	3	2.5	0.2
5 Jan	0	0	0	0	8	18	34	34	2	2.5	0.2
6 Jan	T	0	T	0	11	15	28	31	2	2.2	0.2
7 Jan	0.62	0.62	8.8	7.9	26	26	33	35	4	9.6	0.8
8 Jan	0	0	0	0	15	18	26	29	11	9.0	0.8
9 Jan	0.01	T	0.1	T	9	16	27	29	10	8.5	0.8
10 Jan	1.18	1.36	4.3	2.0	19	21	36	37	11	9.0	1.6
11 Jan	0	0	0	0	11	16	23	24	12	9.0	1.6
12 Jan	0	0	0	0	8	12	18	20	12	9.0	1.6
13 Jan	0	0	0	0	5	12	20	23	12	9.0	1.5
14 Jan	0.17	0.18	1.8	2.0	12	16	24	29	11	10.6	1.4
15 Jan	0.03	0.06	0.5	0.5	8	18	27	29	13	10.5	1.5
16 Jan	0.03	0.03	0.2	0.5	4	9	22	25	13	11.0	1.4
17 Jan	0	0	0	0	0	4	13	15	13	11.0	1.4
18 Jan	0	0	0	0	-2	0	11	14	13	11.0	1.3
19 Jan	0	0	0	0	8	9	28	30	12	-	1.2
20 Jan	0	0	0	0	18	20	36	39	11	-	1.1
21 Jan	0	0	0	0	18	25	30	33	10	-	1.1
22 Jan	0	0	0	0	9	12	22	26	9	-	1.1
23 Jan	0	0	0	0	5	10	30	31	9	-	1.0
24 Jan	0.04	0.04	0.5	0.5	9	18	33	36	9	7.0	1.0
25 Jan	0.17	0.23	3.2	2.5	27	29	37	41	13	7.5	1.2
26 Jan	0	0	0	0	14	24	31	34	11	-	1.2

Table X (cont'd)

	Precipitation (in. of water)		Snowfall (in.)		Temperatures ([F) Minimum		Temperatures ([F) Maximum		Depth of snow on the ground (in.)		Water equivalent (in.)
	NWSO	TWS	NWSO	TWS	NWSO	TWS	NWSO	TWS	NWSO	TWS	NWSO
27 Jan	0.02	0.01	0.2	0.1	16	22	30	34	11	-	1.9
28 Jan	0.14	0.03	0.1	0.1	-4	8	43	46	10	-	1.9
29 Jan	T	0.02	0.1	0.2	4	5	14	15	9	-	2.0
30 Jan	0	0	0	0	1	8	18	19	9	-	2.0
31 Jan	0	0	0	0	5	9	21	22	8	-	2.0
1 Feb	T	T	T	T	10	18	29	30	8	-	2.0
2 Feb	0	0	0	0	6	15	27	29	8	-	2.0
3 Feb	0.04	0.03	0.4	0.6	10	19	33	34	8	-	2.0
4 Feb	T	0	T	0	23	27	37	39	8	-	2.0
5 Feb	0.29	0.35	3.6	5.0	17	19	30	34	9	9.5	2.3
6 Feb	0	0	0	0	11	14	22	24	12	-	2.3
7 Feb	0	0	0	0	14	16	24	28	11	-	2.3
8 Feb	0	0	0	0	13	20	33	35	11	-	2.2
9 Feb	0	0	0	0	1	14	36	38	11	-	2.0
10 Feb	T	T	T	T	24	32	41	44	10	-	2.0
11 Feb	0	0	0	0	20	26	49	52	9	-	1.8
12 Feb	T	T	T	0	37	39	44	44	6	-	1.0
13 Feb	0.05	0.03	0	0	32	38	40	47	3	-	1.0
14 Feb	0	0	0	0	32	37	43	47	3	-	0.9
15 Feb	0.06	0.01	0.4	0.1	20	23	36	39	2	-	0.8
16 Feb	0	0	0	0	11	14	25	28	2	-	0.8
17 Feb	0	0	0	0	6	11	23	25	2	-	0.8
18 Feb	0	0	0	0	7	13	31	34	2	-	-
19 Feb	T	T	T	T	21	26	38	41	1	-	-
20 Feb	0.40	0.33	4.5	4.0	24	29	32	34	1	4.5	0.7
21 Feb	0.01	0.02	0.2	0.2	15	21	32	33	5	-	1.3
22 Feb	T	T	T	T	6	15	36	39	5	-	1.3
23 Feb	0	0	0	0	23	31	42	47	4	-	1.3
24 Feb	0.62	0.41	0	0	33	35	37	41	3	-	1.3
25 Feb	1.13	1.47	0	0	37	39	50	53	2	-	1.0
26 Feb	0	0	0	0	32	39	47	53	2	-	0.9
27 Feb	0.13	0.14	0	0	30	36	45	49	2	-	-
28 Feb	0.08	0.05	0	0	29	34	41	43	T	-	-

day. It is likely, then, that little daytime melt and runoff occurred. The depth of snow on the ground at both weather stations substantiates this. The water equivalent values at NWSO are somewhat confusing since an inexplicable "jump" occurs on 27 January even though very little precipitation is reported then. For whatever reason this occurred, the 2.3 in. (12.0 psf) of water equivalent reported on 5 February at NWSO agrees with our estimate. Downtown it seems likely that slightly more water equivalent remained in the snowpack due to the greater total precipitation. We estimate that the snowpack water equivalent at the arena was 2.5 in. (13.0 psf) on 5 February. We expect that this was the maximum value the arena roof was likely to have experienced prior to January 1978.

CONCLUSIONS

We have calculated the probable roof snow load for the Civic Center Arena at the time of the collapse using four different approaches. Each approach yields an estimate of the load from a combination of available data and assumptions based on our experience. Results are tabulated below:

From TWS weather records	-	14.0 psf
From NWSO weather records	-	14.6 psf
From NWSO snowpack water equivalent	-	13.8 psf
From snow load measurements	-	17-18 psf
From rain-on-snow analysis	-	14 psf

Recent studies[8,9] have shown that rain gauges do not catch all precipitation when accompanied by wind. The amount of undercatch varies with the type of precipitation, wind speed, temperature, and the type, exposure and shielding of the gauge. Undercatches of as much as 70% have been reported for snowfall and 15% for rainfall when windspeeds are 20 mph for the type of gauges used in this study. Both storms considered in this study had a mixture of precipitation types and windspeeds. If we assume that the rain gauge catch was 20-30% less than the true value, the three snow load estimates based on weather records would increase from about 14 psf to 17-18 psf. Considering this and all other evidence we conclude that the snow load on the roof of the Hartford Civic Center Arena at the time of collapse was a uniform load of 15 to 18 psf. Past records indicate that this was the heaviest load the roof was subjected to since its construction in 1974.

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